FINAL REPORT

Review of the Feasibility of Oxygen Addition or Accelerated Upwelling in Hood Canal, Washington

June 13, 2005

Presented to:

Puget Sound Action Team
Office of the Governor

Presented by:

Donald E. Wilson, Ph.D.
Brown and Caldwell

Marc Beutel, Ph.D., P.E
Department of Civil and Environmental Engineering, Washington State University

Cover map: Bathymetry/topography adapted from D.P. Finlayson (2005) Combined bathymetry and topography of the Puget Lowlands, Washington State. University of Washington (http://www.ocean.washington.edu/data/pugetsound/)

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OFFICE OF THE GOVERNOR
P.O. BOX 40900
OLYMPIA, WA 98504-0900
PSC 200402

PRESENTED BY:

DONALD E. WILSON, PHD
BROWN AND CALDWELL
9620 SW BARBUR BOULEVARD
SUITE 200

PORTLAND, OR 97219

MARC BEUTEL, PH.D., P.E.
DEPARTMENT OF CIVIL AND
ENVIRONMENTAL ENGINEERING
WASHINGTON STATE UNIVERSITY
P.O. BOX 642910
PULLMAN, WA 99164-2910

BROWN AND CALDWELL

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EXECUTIVE SUMMARY

Hood Canal is a water body known to experience low dissolved oxygen (DO) events, particularly in the Great Bend area between Potlatch State Park and Hoodsport (Figure 1-1). Anthropogenic nutrient loadings carried by the four canal river systems, the discharges of numerous onshore septic systems, the sanitary wastes of recreational boaters, and other sources cause continual algal blooms in the surface water during the summer months. As the algae die off; the decomposing cells sink into the deep waters of the canal consuming oxygen and creating low oxygen conditions or hypoxia.

In 2004, the Puget Sound Action Team (Action Team), issued grants to 14 organizations to conduct innovative and effective projects to help increase DO concentrations in Hood Canal and improve the quality of water for marine life. A majority of the grants went to increase public awareness of the problem and to implement Best Management Practices (BMPs). BMPs are effective, but normally require a number of years to achieve maximum results. Recent observations indicate that the canal has not recovered from last year's oxygen depletion, which will further aggravate the situation next summer. An expedient solution currently under consideration, and the focus of this report, is whether the oxygen depleted waters of the canal can be oxygenated by mechanical means.

This project was constrained by the need to maintain the stratification of the canal to both inhibit the introduction of deep water nutrients into surface waters where they can stimulate algal growth and preserve the existing cold-water and warm-water habitats. This restriction narrowed our investigation to hypolimnetic Bubble Plume diffusers and Speece Cones. Aeration systems are less efficient and more apparatus-intensive than oxygenation systems. In such a dynamic system (currents, aggressive weather, and corrosive saline environment) such as the canal, a goal of any aeration/oxygenation system should be to minimize the amount of physical apparatus in contact with the canal waters.

Unfortunately, our review of the oxygenation literature identified no similar studies involving deep, marine fjordal systems. The lack of a direct test case, adds additional uncertainty to our analysis. Preliminary calculations indicate that oxygenation of the whole Canal which has a volume of approximately 1.8×10^{10} m^3 is unfeasible, because of the volume of oxygen required. However, for targeted areas of ecological significance having dimensions of approximately 1 $mile^2$ by 20 meters deep, our analysis indicates the Bubble Plume and Speece Cone technologies are both viable oxygenation options.

The Bubble Plume System will require less capital equipment and less engineering than the Speece Cone alternative. However, numerous implementation questions remain, which may be resolved by convening a panel of experts familiar with Hood canal and its hypoxia problems.

We estimate that a 30-day pilot project using bubble plume technology would cost in the neighborhood of $400,000 (includes a 25% contingency) and that the equipment would occupy less than a quarter acre of shoreline. For the same cost, we believe that the equipment could also be mounted upon a self-propelled barge which would allow a number of locations to be oxygenated during the study period.

CHAPTER 1
PROBLEM STATEMENT

Hood Canal experiences summertime low dissolved oxygen (DO) events, particularly in the Great Bend area between Potlatch State Park and Hoodsport (Figure 1-1). During the dry months between May and October, little net exchange of tidal water occurs and the system becomes stratified as the result of solar heating of the fresher, oxygenated surface layer. Although climatic changes, variations in freshwater inputs, and basin geometry probably contribute to the overall effect, the DO depletion appears to be mainly the result of cultural eutrophication. That is, anthropogenic nutrient loadings carried by the four canal river systems, the discharges of numerous onshore septic systems, the sanitary wastes of recreational boaters, and other sources cause continual algal blooms in the surface water during the summer months. As the algae die off; the decomposing cells sink into the deep waters of the canal consuming oxygen and creating low oxygen conditions or hypoxia. Aquatic organisms must either flee or die under these conditions, and summer fish kills are now commonplace. Unfortunately, the human population of the lower canal is at a maximum during this most sensitive period because of maximized occupancy of vacation rentals and increased marine recreational activity.

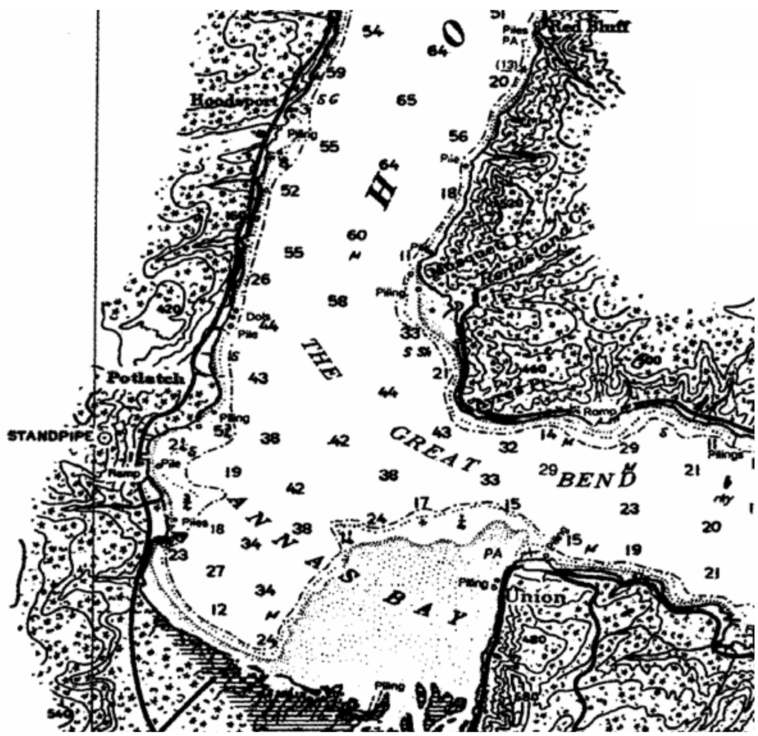


Figure 1-1. Great Bend Area of Hood Canal, Puget Sound, Washington

Hood Canal's circulation pattern has until recently contained or minimized the oxygen depletion process. A glacially-generated shallow sill in the vicinity of South Point impedes the direct communication of canal deep waters with the basin waters of Admiralty Inlet and beyond—i.e., a typical fjordal system in which freshwater from rivers, notably the Skokomish River, override the cold saline marine waters in the canal. Although there is some mixing of the water masses via rain and wind events and entrainment, the fresher surface waters flow northward out of the canal. To compensate for this loss, deep marine water passes over the shallow sill and enters the mouth of the canal. As the marine water moves southward, it is atmospherically isolated and is steadily depleted of DO by plant and animal respiration and bacterial decomposition. Finally, in the area of The Great Bend, the canal shallows and the deoxygenated deep water is pushed to the surface, mixed, and aerated with river discharge, and the resultant water mass then flows to the north.

The residence time of the deep marine water in Hood Canal has been estimated to be between 6 months to a 1 year—a timescale easily overwhelmed by increased summertime nutrient loading. As recent Washington Department of Ecology field data demonstrate, the problem is serious and natural recovery of the system is improbable. Clearly, governmental intervention is necessary.

In October 2004, the Puget Sound Action Team (Action Team), using $800,000 in combined federal and state funding, issued grants to 14 organizations to conduct innovative and effective projects to help increase DO concentrations in Hood Canal and improve the quality of water for marine life. A majority of the grants went to increase public awareness of the problem and to implement Best Management Practices (BMPs). BMPs are effective, but normally require a number of years to achieve maximum results. Meanwhile, recent observations indicate that the canal has not recovered from last year's oxygen depletion, which will further aggravate the situation next summer. An expedient solution currently under consideration, and the focus of the Action Team's recent Request for Proposals (RFP), is whether the oxygen-depleted waters of the canal can be oxygenated by mechanical means.

Scope of Work

Brown and Caldwell responded to the above-cited RFP issued December 10, 2005, and was later selected by the Action Team as the most responsive submittal. The Scope of Work specified that Brown and Caldwell complete the following activities:

- Develop a list of possible methods to add oxygen to some portion of the canal or to accelerate upwelling, to be reviewed and approved by the Action Team staff.
- Compile a list of comparable sites where aeration or induced upwelling is being used to address hypoxia, the methods being used, how successful they are, and contact information.
- Prepare a literature-based review of the possible methods, describing their operation and whether they have the potential to improve conditions in Hood Canal.
- For each of the most promising methods, selected in consultation with Action Team staff, develop a scenario applying each method to Hood Canal, including calculation of the likely change in Hood Canal and approximate costs.
- Prepare a draft report of review by Action Team staff and reviewers selected by the Action Team.

- Provide a final report to the Action Team in Microsoft Word Format for publication by the Action Team.

Screening Criteria for Aeration Methodologies

Table 1-1, at the end of this chapter, was prepared from the information contained in Appendices A and B and summarizes those technologies available to the project. Table 1-1 was forwarded to the Action Team for review on February 14, 2005. A conference call was then arranged to discuss and screen the methodologies listed therein and select a subgroup for further study. This conference call occurred on February 23, 2005. In attendance was John Dohrmann and Duane Fagergren of the Puget Sound Action Team; Tom Mumford, Washington Department of Natural Resources; Wayne Palsson, Washington Department of Fish and Game; Marc Beutel, Washington State University Department of Civil Engineering; and Donald Wilson of Brown and Caldwell. The tabulated list of available mixing/aeration technologies provided by Brown and Caldwell was discussed in light of the following criteria and constraints:

- The hydrodynamics of Hood Canal are not well known at this time.
- Aeration technologies employed should not disrupt the natural stratification of the canal, since artificial upwelling of nutrient-rich waters into the photic zone may cause additional algal blooms.
- The area of greatest DO depletion (Great Bend) has the smallest ambient currents making far-field dispersion of aerated/oxygenated waters difficult.
- Although there is evidence of a summertime DO minimum at mid-depth in the water column, this study will concentrate on aerating/oxygenating deep waters in general.
- Oxygenation is favored over aeration because the latter will increase the concentration of dissolved nitrogen at depth causing potential fish health issues.
- Oxygen can be added to bubble plume aeration/mixing systems to augment the entrained DO concentration.
- A vessel-mounted system may aerate/oxygenate a larger volume of water while underway than is possible by relying solely upon far-field dispersion by currents.
- Aeration technologies that require disproportionate structural engineering and construction costs (e.g., propellers) should be avoided.
- Although aeration technologies may best be applied in the vicinity of the sill to utilize the fjord's natural circulation to spread the aerated/oxygenated waters southward, the existing Naval Operating Area may preclude this option.

- Selected technologies must plan to accommodate biofouling and corrosion.

After discussion, the group selected two technologies for continued study. They are:

1. An unconfined bubble plume system using air or oxygen with bubble size adjusted to prevent complete mixing of the water column.

2. A contact chamber system (i.e., Speece Cone) using oxygen gas.

However, these two technologies will be studied as both onshore and barge-mounted systems.

It should be mentioned that a suggestion received from the public at large to add ozone to the air/oxygen feed stream was not acted upon since ozone's usual applications (disinfection, odor control, and metals removal) are not appropriate to this study. Ozone injection would disrupt the ecological balance of the targeted portions of the Canal by killing planktonic species. Furthermore, the purchase of the ozonator and the energy needed both to power the unit and cool the ultra violet source would substantially increase project costs (US EPA, 1999). Ozone also poses a human health inhalation risk.

Report Organization

Chapter 1 introduces the project, presents Table 1-1, defines the path forward and describes the organization of the report. Chapter 2 describes the oceanographic conditions of Hood Canal. As stated previously, a screening of the technologies listed in Table 1-1 resulted in the selection of two methods for further study. The applicability and estimated costs for the selected methods in various configurations are described in Chapter 3. Brown and Caldwell's conclusions and recommendations are presented in Chapter 4. Chapter 5 lists reference material consulted in the writing of this report.

Appendix A describes a number of sites somewhat comparable to Hood Canal, although non-marine, at which aeration or induced upwelling has been or is being used to address hypoxia. Appendix B contains a literature-based, historical review of aeration techniques in general. The information contained in Appendices A and B was distilled to develop Table 1-1.

Table 1-1. Hood Canal Mixing/Aeration Technology Matrix

Technology	Description	Advantages/disadvantages	Possible calculations/analysis	Contacts
Artificial circulation				
Propeller Mixing	Large, slow moving propellers (approximately 6 feet diameter, approximately 1 rpm) mounted vertically to promote vertical circulation of water. Unaware of large-scale applications–Beutel doing lit search.	Propellers can move enormous amounts of water horizontally using minimal energy. Ineffective or limited influence when mounted vertically (e.g. Lake Elsinore).	Estimate vertical flow rate from single 6-foot-diameter propeller and compare to rate of exchange between surface and bottom waters. Optimize location.	Brown and Caldwell to contact ITT Flygt rep.; Dr. Mike Anderson, UC Riverside, 909-787-3757, michael.anderson@ucr.edu; Mark Mobley, Mobley Engineering, 865-494-0600, mark@mobleyengineering.com
Bubble Plume Mixing	Compressed air is discharged through diffuser array roughly 20 feet in diameter. Mixing/oxygenation system has been operational in a number of large, deep Swiss lakes (>150 feet) since the early 1980s.	Rate of mixing/entrainment increases with depth. Models exist that can accurately estimate mixing flow rates and oxygen transfer rates.	Examine bubble plume mixing model and estimate flow rate for given depth in canal. Compare to rate of exchange between surface and bottom waters. Optimize location.	Dr. John Little, Virginia Tech, 540-231-8737, jcl@vt.edu; Arno Stoeckli, Kanton Aargau, Switzerland, arno.stoeckli@ag.ch
Other Large-Scale Compressed Air Mixing	Compressed air discharged through perforated pipes or other diffuser systems. Unaware of large-scale applications – Beutel doing lit search.	Simple apparatus. Compressed air commonly used in US lakes for artificial mixing, but limited to relatively shallow systems (<60 feet).	Examine mixing rate for given depth in canal. Compare to rate of exchange between surface and bottom waters. Optimize location.	None to report at this time.
Deep Lake Aeration				
Perforated Pipe	Most US aeration examples are in small lakes that bare little resemblance to large scale of Hood Canal. Two case studies from deep California reservoirs used a system that included a compressor pumped air through perforated PVC pipe suspended 30 feet off of the lakebed from surface rafts.	System may not suitable for open water environment of Hood Canal.	No further analysis?	Dr. Arlo Fast**,** Hawaii Institute of Marine Biology, 808-236-7401
Full-Lift Tube	A full-lift system includes two concentric tubes running the length of the water column. Compressed air is injected in the base of the inner tube, and the aerated water is returned to the bottom of the lake via the outer tube. This system was used in the 1970s in Wahnbach, Germany. Limited use of system in deep US lakes.	Simple system. Levels of dissolved nitrogen will increase in bottom water. System less efficient than using pure oxygen since air only contains 20 percent oxygen.	Estimate oxygen demand in canal. Compare to delivery rate of single tube. Estimate number of tubes and on-shore facilities. Estimate area of influence of single tube based on canal hydrodynamics using CORMIX. Optimize location.	None to report at this time.
Mixox	Finnish system in which oxygen rich surface water is pumped down into bottom of lake. System reportedly successful in some large Finish Lakes (150 feet deep).	System may not be appropriate for salinity stratification in Hood Canal since density difference to difficult to overcome with pumping.	No further analysis?	None to report at this time.

Table 1-1. Hood Canal Mixing/Aeration Technology Matrix (continued)

Technology	Description	Advantages/disadvantages	Possible calculations/analysis	Contacts
Oxygenation				
Contact Chamber Oxygenation	Pure oxygen gas is injected into top of submerged cone along with bottom water which is pumped into cone with submerged pump. Highly oxygenated water is discharged out bottom of cone. System has proven effective in large California reservoir (400,000 acre-feet).	Oxygen transfer rate for given cone size increases with depth–roughly doubles every 40 feet. Small system requirements for large oxygen addition. Rate of oxygen addition easily controlled. Oxygen can be distributed at sediment-water interface. Submersible pump requires submerged electrical line to chamber.	Estimate oxygen demand in canal. Compare to delivery rate of single chamber. Estimate number of chambers and on-shore facilities. Estimate area of influence of single chamber based on canal hydrodynamics using CORMIX. Optimize location.	Dr. Barry Moore, Washington State University, 509-332-5882, bcmoore@mail.wsu.edu; Dr. Richard Speed, Vanderbilt University, 615-343-6328, dick.speece@vanderbilt.edu; Dr. Alex Horne, UC Berkeley, 510-525-4433, anywaters@comcast.net; Rod Jung, East Bay Municipal Utility District, 886-403-2683, rodjung@ebmud.com; Dr. Bill Faisst, Brown and Caldwell, 925-937-9010, bfaisst@brwncald.com
Bubble Plume Oxygenation	Pure oxygen gas is discharged through diffuser array roughly 20 feet in diameter. System has been operational in a number of large, deep Swiss lakes (>150 feet) since the early 1980s.	Can be used as a hybrid system–high airflow rate to induce mixing or lower oxygen gas flow-rate to promote aeration. Oxygenation effects confined to upper water column. Models exist that can accurately estimate mixing flow rates and oxygen transfer rates. No pumps required.	Estimate oxygen demand in canal. Compare to delivery rate of single diffuser array. Estimate number of diffuser arrays and on-shore facilities. Estimate area of influence of single diffuser array based on canal hydrodynamics. Optimize location.	Dr. John Little, Virginia Tech, 540-231-8737, jcl@vt.edu; Arno Stoeckli, Kanton Aargau, Switzerland, arno.stoeckli@ag.ch; Dr. Ellie Prepas, University of Alberta, 780-492-3463, eprepas@ualberts.ca
Linear Diffuser Oxygenation	Pure oxygen gas in slowly discharged through linear diffuser system. Large-scale systems (>100 tons per day of oxygen) in operation by TVA and ACOE in large power generation reservoirs in southern US.	System efficiency increases with increasing depth. No pumps required. Extensive network of diffuser lines required. Oxygen is discharged over wide area. Vertical bubble release may not oxygenate sediments with high oxygen demand.	Estimate oxygen demand in canal. Estimate length of required diffuser and on-shore facilities. Optimize location.	Mark Mobley, Mobley Engineering, 865-494-0600, mark@mobleyengineering.com; Rod Jung, East Bay Municipal Utility District, 886-403-2683, rodjung@ebmud.com; ACOE contact?; TVA contact? – Beutel tracking down.
Shore-Based Oxygenation Systems	Pure oxygen gas is dissolved into side stream of water body with u-tube or venturi on shore. Highly oxygenated side stream is discharged back into water body.	Majority of facilities are on shore and out of water. Pumping required since water must be withdrawn and discharged back into water body.	Estimate oxygen demand in canal. Compare to delivery rate of single shore-based system. Estimate number of systems and facilities. Estimate area of influence of single system based on canal hydrodynamics using CORMIX. Optimize location.	Dr. Richard Speed, Vanderbilt University, 615-343-6328, dick.speece@vanderbilt.edu; B. Greenop, Water and Rivers Commission, Western Australia,

Table 1-1. Hood Canal Mixing/Aeration Technology Matrix (continued)

Technology	Description	Advantages/disadvantages	Possible calculations/analysis	Contacts
Barge-Based Oxygenation Systems	Large mobile barge can be used to dissolve pure oxygen gas into specific area of water body that is low in DO. Oxygen is either produced or stored on barge. Method has been used successfully on the River Thames in London for decades. Oxygenation barges also in use China.	System is mobile and can discharge oxygen where and when it is needed.	Estimate oxygen demand in canal. Compare to delivery rate of barge-based system. Estimate area of influence of single system based on canal hydrodynamics using CORMIX.	Dr. Alex Horne, UC Berkeley, 510-525-4433, anywaters@comcast.net; UK Thames River Authority; http://www.esemag.com/0302/china.html
Novel Technologies and Approaches				
Sed Con Technologies, Inc.	Uses large water jets to inhibit sediment from accumulating in ship berthing areas.	Might be adapted		www.scoursystrems.com

Note: See http://www.esemag.com/0302/china.html for China river oxygenation in Suzhou Creek, a highly polluted stream that flows through Shanghai.

CHAPTER 2
LOWER HOOD CANAL OCEANOGRAPHIC CONDITIONS

The following sections describe the oceanographic conditions of the Lower Hood Canal. This data was used in our modeling of the effectiveness of the various mechanical oxygenation systems on the canal. We digitized portions of National Ocean Service navigational charts 18441 and 18448 to obtain a XYZ (latitude, longitude, depth) file of the Canal. The surface area and volume of this three-dimensional model was the estimated using the surface mapping software program Surfer® Version 7.0 (Golden Software) as 2.4×10^8 m^2 and 1.8×10^{10} m^3, respectively.

Stratification

Water quality data obtained for Washington Department of Ecology (WDOE) Station HCB004 is considered representative of the situation that exists in the Great Bend area during the summer low river flow season. The station is located immediately South of Sisters Point in a water depth of 53 meters (Figure 2-1). Numerous data sets are available for this station on WDOE's web page located at www.ecy.wa.gov/apps/eap/marinewq/mwdataset.asp?staID=68, but we selected the data from July 23, 2002 as most representative of the Great Bend area.

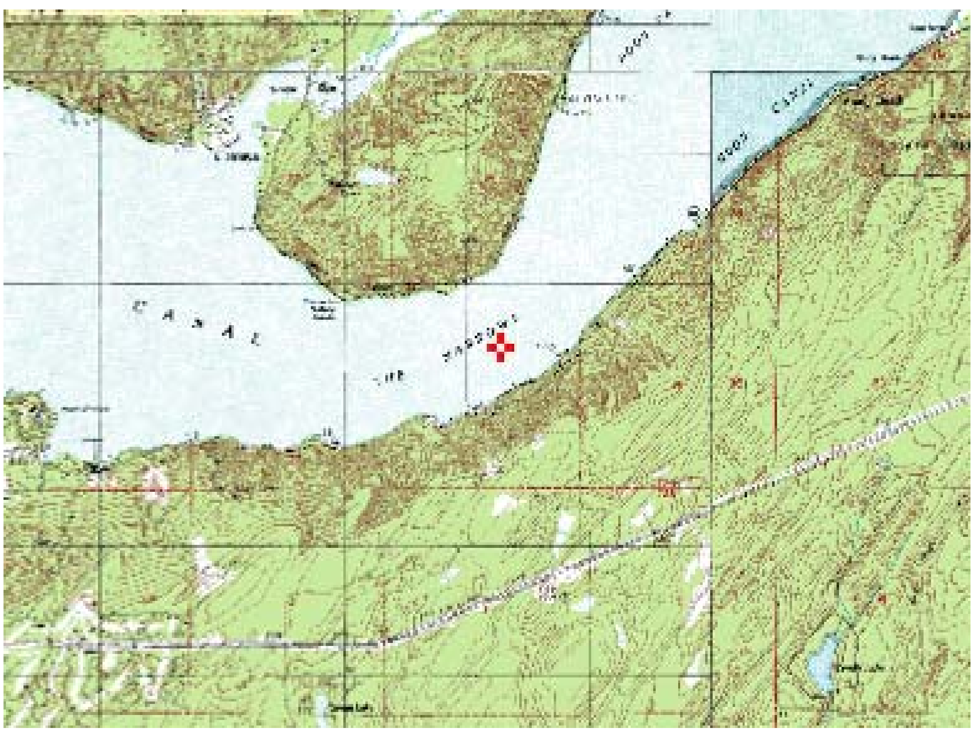


Figure 2-1. WDOE Station HCB004

Figure 2-2 presents depth profiles for temperature, DO, salinity, and Sigma-t for Station HCB004 for July 23, 2002. Although stratification of the water column is evident, the temperature and salinity curves indicate a complex situation of possible solar heating coupled with freshwater input. The thermocline terminates at approximately 7-meters water depth. There is evidence of a few meters thick intermediate water layer existing immediately below the thermocline.

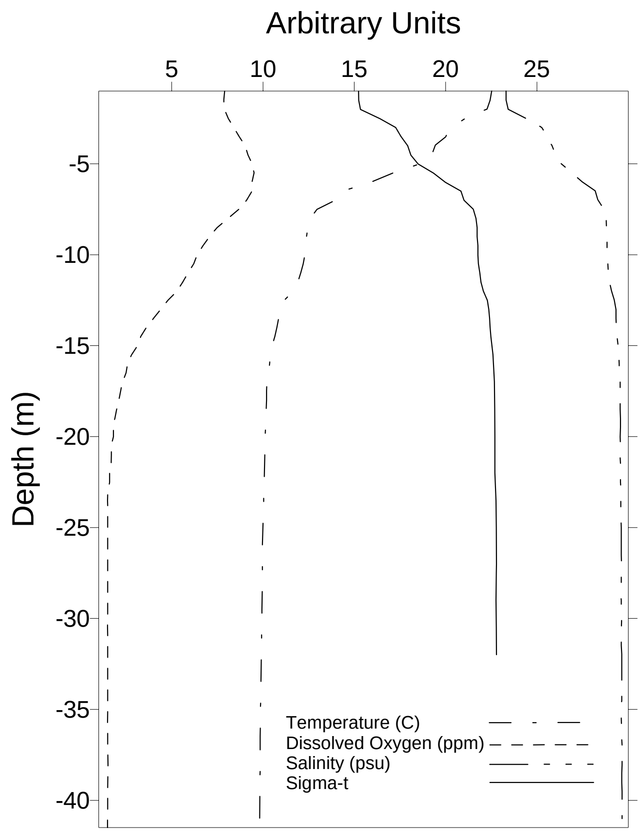


Figure 2-2. Water Quality Data - Station HCB004
July 23, 2002, Great Bend, Sisters Point, Water Depth 53 m
Washington State Department of Ecology

This intermediate water layer is slightly warmer and slightly less saline than the deep canal bottom water.

The DO profile exhibits a pronounced metalimnetic oxygen maximum (Wetzel, 1983). The water at a depth of 5.5 meters is 102 percent saturated with respect to oxygen. Such maxima are nearly always the result of oxygen produced by algal populations that develop more rapidly then they are lost from the pycnocline by sinking.

Moving deeper into the water column, the concentration of DO is significantly reduced, approaching anoxic conditions below 20 meters (approximately 1.5 milligrams oxygen per liter [mg O_2 /L]). This condition is intolerable to most animals. Most fish cannot survive, even at low temperatures, at less than 2 mg O_2/L. Stratification effectively inhibits the exchange of oxygen between the bottom water and the atmosphere, and respiration and decomposition processes exert an oxygen demand. A rough calculation of the deep water biological oxygen demand was made using the difference in hypolimnetic DO concentrations at two water quality stations in Hood Canal, the distance in miles between those stations, and an assumed southerly velocity of 2.5 centimeters per second for the deep water. The oxygen demand thus calculated was approximately 0.1 mg O_2/L/day, a value which is usually associated with good water quality conditions.

Currents

Hood Canal is a fjord-type estuary, highly stratified with fresh water flowing out over a nearly uniform deep saline layer. The net flow of deep water is toward the head. Few current meter data exist for Hood Canal. Recently, the U.S. Geological Survey (USGS) was asked by Congress to become actively involved in the study of the causes of low DO concentrations in Hood Canal. Among their focused studies was the 30-day deployment of two, bottom-mounted acoustic Doppler current profilers (ADCP) in the Great Bend region during summer, 2004. This data is not yet available (personal communication, Anthony Paulson, February 8, 2005). However, prior to the fixed instrument deployment, four current transects were conducted using a vessel-mounted ADCP system. These data were made available to this report. Transects were conducted on July 7, 2004 at approximately 11 a.m. This time period corresponds to the maximum monthly ebb currents as predicted by the Hoodsport tide tables. The tide fell from a 9.6-foot high to a -1.0-foot low. Figure 2-3 presents the approximate tracklines for transects 3 and 4. The current profiles corresponding to these transects are shown in Figure 2-3.

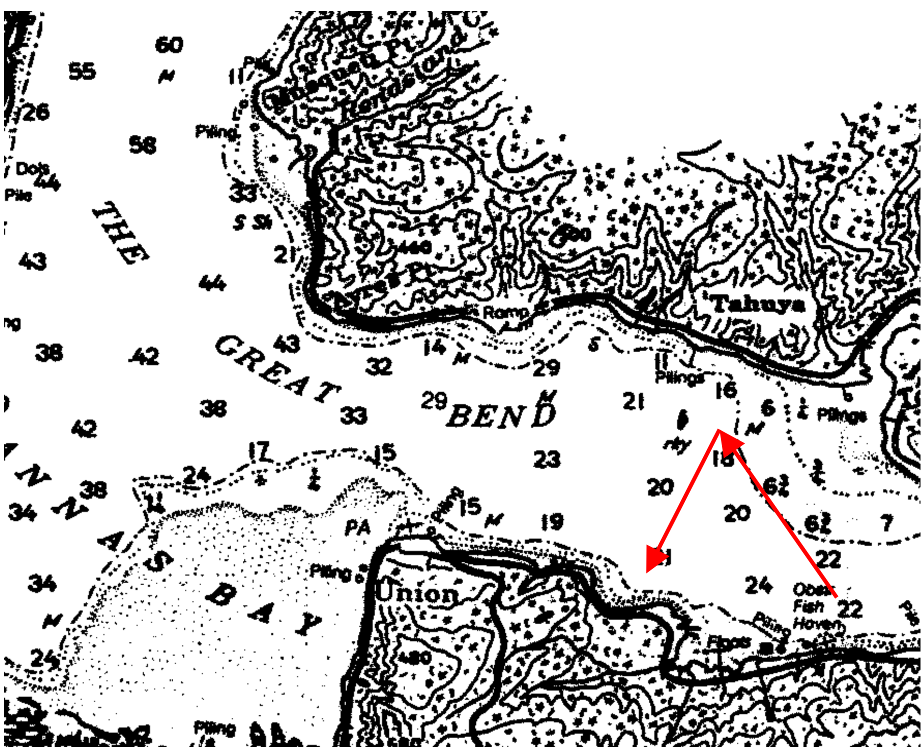


Figure 2-3. Great Bend ADCP Transects 3 and 4, July 7, 2004, USGS

Union, located at the head of Hood Canal, has a tidal range of 10 to 12-feet. Water depths in this area are on the order of 30 to 50 meters (90 to 150 feet) mean low low water. Thus the tidal prism is typically less than 10 percent of the resident water volume. To produce the observed tides in a dead-end system, current flows need not be high. This is substantiated by the USGS current data of Figure 2-4. Current speeds on the spring ebb are less than 0.5 knots at all depths along both transects except for a lens of water that lies to the south in the vicinity of the thermocline. This lens apparently has an ebb velocity of between 0.75 to 1.0 knots and is apparently the main tidal flow. No simultaneous water quality data were taken during the transects so that the relation of the flow to the thermocline is unknown. However, the WDOE water quality data discussed above indicate that the usual position of the dry weather thermocline in the Great Bend is between 3 to 7 meters below the surface.

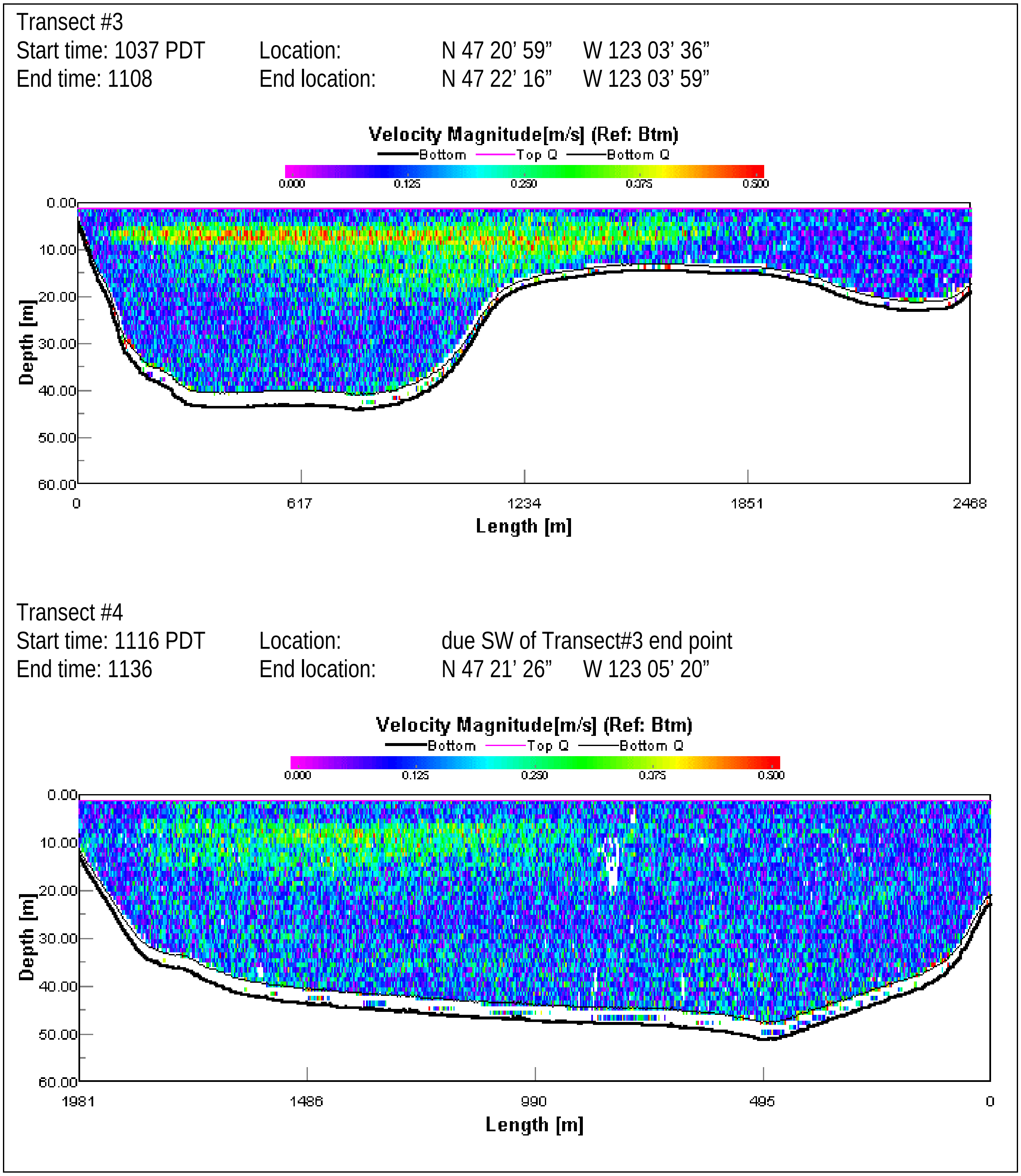


Figure 2-4. Current Data, USGS Transects 3 and 4, Great Bend, Hood Canal

CHAPTER 3
ANALYSIS OF OXYGENATION ALTERNATIVES

Unfortunately, our review of the oxygenation literature identified no similar studies involving deep, marine fjordal systems such as Hood Canal. The lack of a test case adds further uncertainly to the following analysis.

This project was constrained by the need to maintain the stratification of Hood Canal to both inhibit the introduction of deep water nutrients into surface waters where they can stimulate algal growth, and to preserve the existing cold-water and warm-water habitats. This restriction narrowed our investigation to hypolimnetic bubble plume diffusers and Speece Cones. Aeration systems are less efficient and more apparatus-intensive than oxygenation systems. In such a dynamic system (currents, temperature, aggressive weather, and corrosive saline environment) such as the Canal, a goal of any aeration/oxygenation system should be to minimize the amount of physical apparatus in contact with the canal waters. For example, a recent preliminary evaluation of aeration options for a Lake Onondaga, a large, polluted lake in New York, concludes that one oxygenation cone is equivalent to roughly 8 air-lift aeration units.

The industrial gas industry uses many different units to measure volumes of gas. Table 3-1 below is included to assist the reader with unit conversions. It lists the various conversion equivalents for 2000 lbs of liquid oxygen.

Table 3-1. Oxygen Quantity Conversions			
Pounds (lbs)	2000	Kilograms (Kg)	907.03
Ton (short ton)	1.0	Metric Ton	0.907
Std Cubic Feet (SCF)	24,151.67	Normal Cubic Meters (Nm3)	634.72
Liquid Gallons (Gal)	209.93	Liquid Liters	794.60

Bubble Plume System

For an unconfined bubble plume diffuser system, bubble diameter is the controlling design variable. Large bubbles (approximately 2 millimeters) rising through the water column under buoyancy forces exchange dissolved gas with the surrounding water at rates which are dependent on a number of complex variables, including bubble size, bubble velocity, gas flow rate, diffuser area, entrained water velocity, and ambient oxygen and nitrogen levels. The bubble plume entrains and moves water from one density layer to another, mixing the system and destroying the present thermal structure. At the surface, gas is lost to the atmosphere with bubble breaking, while entrained water falls back to a depth of neutral buoyancy then spreads horizontally.

To counter the mixing, the bubble size generated by the diffuser must be sufficiently small so that the bubble dissolves in a predetermined height of the water column rather than rising to the surface. When a bubble dissolves, the total gas transferred becomes purely dependant upon the initial gas composition and the solubility coefficient. Diffusivity, a length of the path the bubble takes in a turbulent regime as it rises to the surface, affects how long it takes the bubble to dissolve. For example, a 5 mm diameter clean bubble containing air released at a depth of 22 meters would dissolve after approximately 200 seconds and after rising approximately 5 meters. It is apparent then that these systems are most efficient when pure oxygen is used as the gas rather than compressed air which is only 20 percent oxygen. Pure oxygen gas (97 percent) produces an area of extremely high dissolved oxygen in the vicinity of the diffuser which is then dispersed by ambient currents.

A schematic illustration of a typical unconfined bubble plume system is presented in Figure 3-1. If liquid oxygen is used, there is no need for a compressor since the vaporization process will develop sufficient pressure by itself. This is not the case if onsite oxygen production is selected using a vacuum pressure swing adsorption (VPSA) system. A VPSA system includes a rotary-lobe feed air blower, vacuum blower (two bed systems only), one or two adsorbent vessels, an oxygen surge tank, switching valves and computer controls.

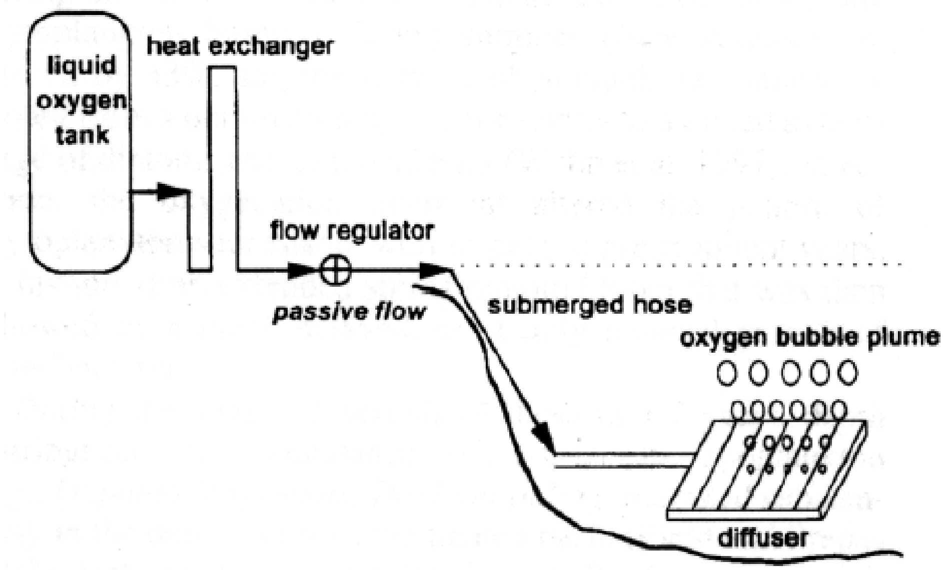


Figure 3-1. Bubble Plume System

In the single-bed system, the blower draws in air, compresses it, and sends it to the adsorbent vessel (synthetic zeolites) to remove impurities, leaving 90 to 94 percent pure oxygen as the product. The adsorbent is then regenerated as the blower removes gas by reducing the pressure inside the vessel. The waste gas (nitrogen, water, and carbon dioxide) is then discharged into the air. Since oxygen is not produced during regeneration, the system includes a low-pressure surge tank to allow for continuous oxygen supply.

Although a number of diffuser materials are available, we believe that simple garden soaker hose would be suitable for Hood Canal. The hose comes in 100-foot lengths, is inexpensive and manageable, and produces the small bubble diameters needed.

At our request, Vickie Singleton of the Virginia Polytechnic Institute (VPI) in Blacksburg, Virginia modeled our requirements (7 ºC, 30 ppt salinity) with the Institute's Discrete Bubble Plume Model and found that with a typical bubble plume system generating 2-millimeter-diameter bubbles, we can inject about 1,300 kilograms (1.4 tons) of oxygen per day at a flow rate of 25 cubic feet per minute at 100 percent efficiency in a water column depth of around 20 to 30 meters. The VPI model is independent of diffuser geometry. The calculation holds for bubble plume systems using either circular geometry as shown in Figure 3-2 or 600 linear feet of soaker hose.

The total pressure at any depth is equal to the force of the water above plus atmospheric (atm) pressure. Since every 10-meters of seawater depth equates to a pressure increase of 1-atm, and since the solubility of a gas in water at a given temperature is a function of the partial pressure of that gas divided by its Henry's Law constant (K_{O2} = 756.7 atm/moles/liter at 25ºC), we can calculate the influence of injection depth on DO concentration. For pure oxygen gas injected into seawater (25ºC) at a depth of 20 meters, the theoretical DO concentration is estimated as 124 mg/liter (ppm). At 50 meters, this concentration is calculated to be 247 mg/liter (ppm). Clearly, the deeper the injection depth, the more tons of oxygen can be added to the system.

A picture of a diffuser array used to oxygenate a number of lakes in Switzerland with roughly a similar delivery rate as that noted above (1.4 tons per day) is shown in Figure 3-2. In the photo, the circular diffuser array (25-ft diameter) has been brought to the surface for maintenance; it is typically submerged on the bed of the lake at a depth of roughly 60 meters. See Appendix A, Section A1.3 for a detailed discussion of the Swiss oxygenation case study.

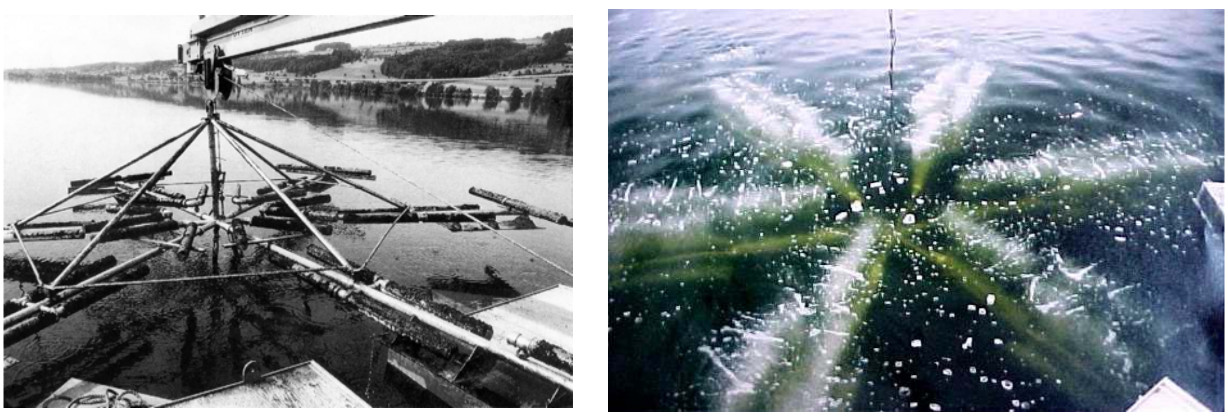


Figure 3-2. Typical bubble plume diffuser arrays used to oxygenate Swiss lakes (Diffuser array is submerged at the bottom of the lake [~60 meters] during operation)
Photos courtesy of the Swiss Federal Institute for Environmental Science and Technology, Kastanienbaum Limnological Institute.

An alternative diffuser system has been developed by researchers with the Tennessee Valley Authority. The system includes a linear diffuser consisting of garden soaker hose. The hose is fed pure oxygen gas from an onshore facility. The line includes buoyancy chambers that can be filled or emptied with water or air from shore. Operators can remotely control the buoyancy of a diffuser, and easily deploy or retrieve it as need. Once in position, the buoyancy of a diffuser is made slightly positive, causing the frame to float above attached weights resting on the reservoir bottom. The main difference with the bubble plume system is that linear diffuser system weeps oxygen bubbles out at a fairly slow rate, thus long linear distances of the linear diffuser are required. For example, to deliver 1.4 tons per day of oxygen, which is equivalent to one typical bubble plume diffuser array, roughly 500 feet of linear diffuser line would be required. Typical oxygen delivery rates range from

0.1 to 0.5 tons of oxygen per 100 feet of linear diffuser. The cost of the diffuser component of the linear diffuser system is approximately $45 per foot. See Appendix A, Section A1.4 and A1.7 for a detailed discussion of the linear diffuser oxygenation case studies.

Calculation of the areal extent or volume of Hood Canal water that would be oxygenated by the unconfined bubble plume is difficult in that the plume is not the type that can be modeled by Environmental Protection Agency (EPA)-approved plume models such as CORMIX or Visual Plumes which are driven by momentum and buoyancy. The bubble plume, prior to its dissolution, would impart some momentum to the waters surrounding the diffuser and possibility set up a circulation cell of small but unknown dimensions. However, the main spreading of the oxygenated waters would be by ambient tidal currents. As mentioned previously, tidal current information in Hood Canal is confined to a recent U.S. Geological Survey acoustic Doppler current profiler profiling study in the Great Bend. Even at observed current speeds of 0.5 knots, a large volume of water would be exposed to the oxygenated plume during a tidal cycle. We consider these systems appropriate for targeted areas of the Canal on the order of 1 mile^2 by 20 meters deep.

Oxygen gas currently sells for $0.40 to $0.50 per 100 standard cubic foot. This equates to $97 to $120 per ton (personal communication, Air Liquide, February 15, 2005). This does not include the cost of delivery to Hood Canal or of the containment vessel, heat exchanger and associated piping. Containment vessels of 6,000-gallon capacity can be leased for $800 per month. Evaporators are also relatively inexpensive to lease.

At an injection rate of 1.4 tons per day, a 30-day test period would cost approximately $5,000 for the gas alone. If a higher injection rate is required, the costs scale appropriately. In contrast, a 1-ton capacity pressure swing oxygen generator would cost approximately $75,000 (personal communication, Dick Speece, March 10, 2005). We estimate that a pilot project using bubble plume technology would cost in the neighborhood of $400,000 and occupy less than a quarter acre of shoreline.. A 25% contingency is included in the cost estimate.

Another option is to barge mount the bubble plume system. We have identified a self-propelled barge located in Seattle of approximately 100-feet length that has sufficient deck space to accommodate the equipment as well as provide living quarters for the crew and project personnel. We estimate the cost of the barge concept to be roughly the same as the stationary option, although the mobility of the barge would allow a number of Canal sites to receive treatment.

A barge system has a number of potential advantages over a permanent installation of a bubble plume diffuser array. The main advantage is that the depth and lateral position of oxygen injection could be varied daily, or even hourly. In addition, the diffuser array could be stored above water during non-use, thereby limiting biofouling of the diffusers and facilitating regular maintenance.

Speece Cone

The Speece Cone is a counter-current system in which water is pumped downward through a cone-shaped chamber placed either on the lake bottom or on shore. Air or oxygen is also injected into top of the cone, where the gas bubbles rise counter to the downward water flow. Oxygenated water is discharged through an exit port at the cone bottom and into a diffuser line. The combination of countercurrent flow and hydrostatic pressure creates a high-efficiency system for solubilization of oxygen in water. Figure 3-3 is a schematic illustration of the submerged system installed in Camanche Reservoir in California. A similar system was installed in Newman Lake, Washington. See Appendix A, Sections A1.6 and A1.8 for detailed descriptions of these oxygenation case studies.

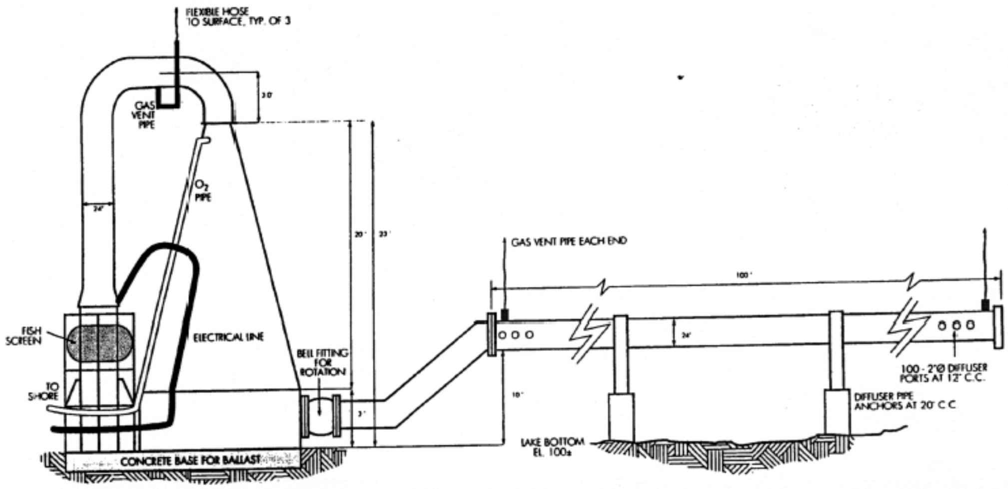


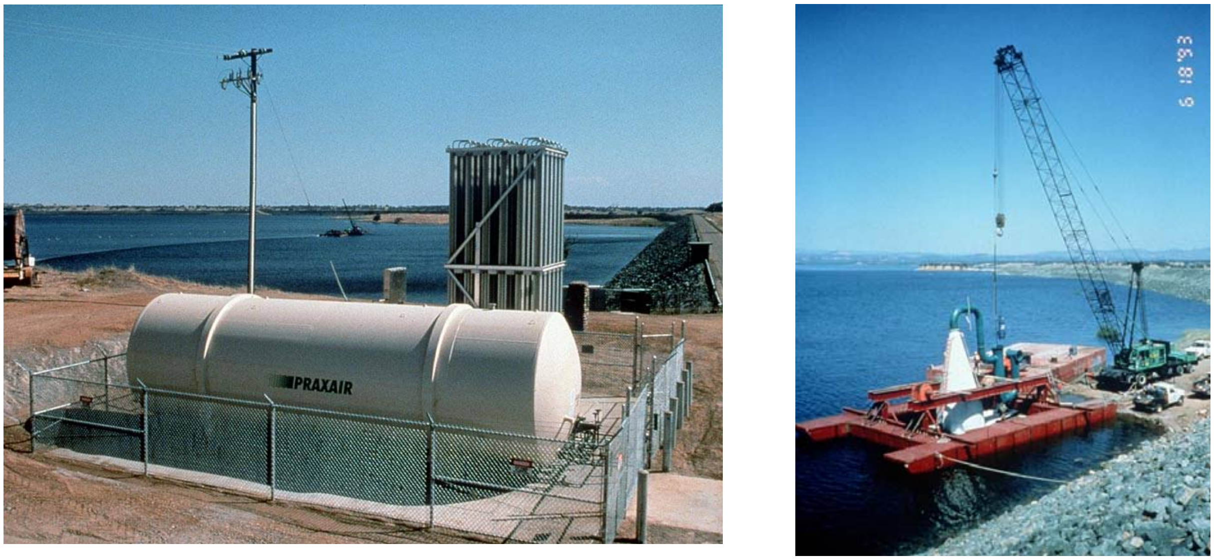
Figure 3-3. Typical Speece Cone System

The Speece Cone's major components are listed in Table 3-1.

Table 3-2. Typical System Specifications for a Speece Cone

Cone volume	11.1 cubic meters (315 cubic feet)
Cone height	4.6 meters (15 feet)
Oxygen delivery	1,360 kilograms per day (3,000 pounds per day)
Duel air/separation oxygen generators	680 kilograms per day (1,500 pounds per day) each
Duel rotary screw compressors	50 hp each
In-lake water pump	40 hp at 0.73 cubic meters per second (21 ft^3 sec)
Distribution manifold	31 meters (100 feet) w/5 cm ports at 60 cm spacing

Figure 3-4 shows photographs of the cone and on-shore facilities for the Camanche Reservoir installation in California.



Onshore facilities including LOX storage tank and evaporator

Installation of the cone which was on the lake bottom at a depth of roughly 30 meters.

Figure 3.4 – Camanche Reservoir
(*Photos courtesy of Dr. Alex Horne, UC, Berkeley*)

The main advantage of the Speece Cone over the bubble plume system is that there is more control over where the oxygen is injected into the aquatic ecosystem, both vertically and horizontally. Since the cone sends out a highly oxygenated discharge horizontally into the water, it is especially applicable in shallow systems where destratification must be avoided, or where bottom sediments must be oxygenated to inhibit the release of reduced compounds from anoxic sediments. The main disadvantage of the system is that it utilizes a submerged pump and electricity must be feed underwater to the Speece Cone system. This can be logistically difficult in some cases. In a marine environment, the cone system may be more susceptible to biofouling than the diffuser system.

The cone system uses oxygen gas so that the gas generation discussion in the bubble plume section also applies. With the cone system, water is jetted from the diffuser so that the plume models Cormix and Visual Plumes are applicable. However, as seen in Figure 3-2, the intake water is essentially at the same depth (density) as the discharge. Since no heat has been added in the process, there are no buoyancy forces acting on the plume so that initial mixing is solely a function of the discharge's jet momentum. Following initial dilution, ambient tidal currents will later cause far-field dispersion.

The Camanche Cone was modeled using EPA's Visual Plumes, version 1.0, using the specifications listed in Table 3-1 and the ambient water quality conditions for the Washington Department of Ecology's (WDOE's) Hood Canal Station HCB004 for July 23, 2002. It was assumed that diffuser was at the 35 meter depth in 75 meters of water, and that the discharged water contained 200 milligrams oxygen per liter. Ambient currents were on the order of 16 centimeters per second (0.3 knots) perpendicular to the diffuser. Under these circumstances, the angle of the discharge ports is important. Without a buoyancy effect, the jet is the mechanism by which the plume is introduced into the water column.

If a momentum plume of some average density (ρz) is introduced into a shallower depth in a stratified water column, the plume will rise until frictional effects overcome the velocity of its rise. The plume will then be denser than the surrounding waters and will sink to return to its equilibrium density level. In this way, the plume will undergo a wavelike (Brunt-Vaisala) oscillation, passing repeatedly through the trapping depth. The angle of the injection ports is important since it controls the height of the jet's penetration into the less dense waters.

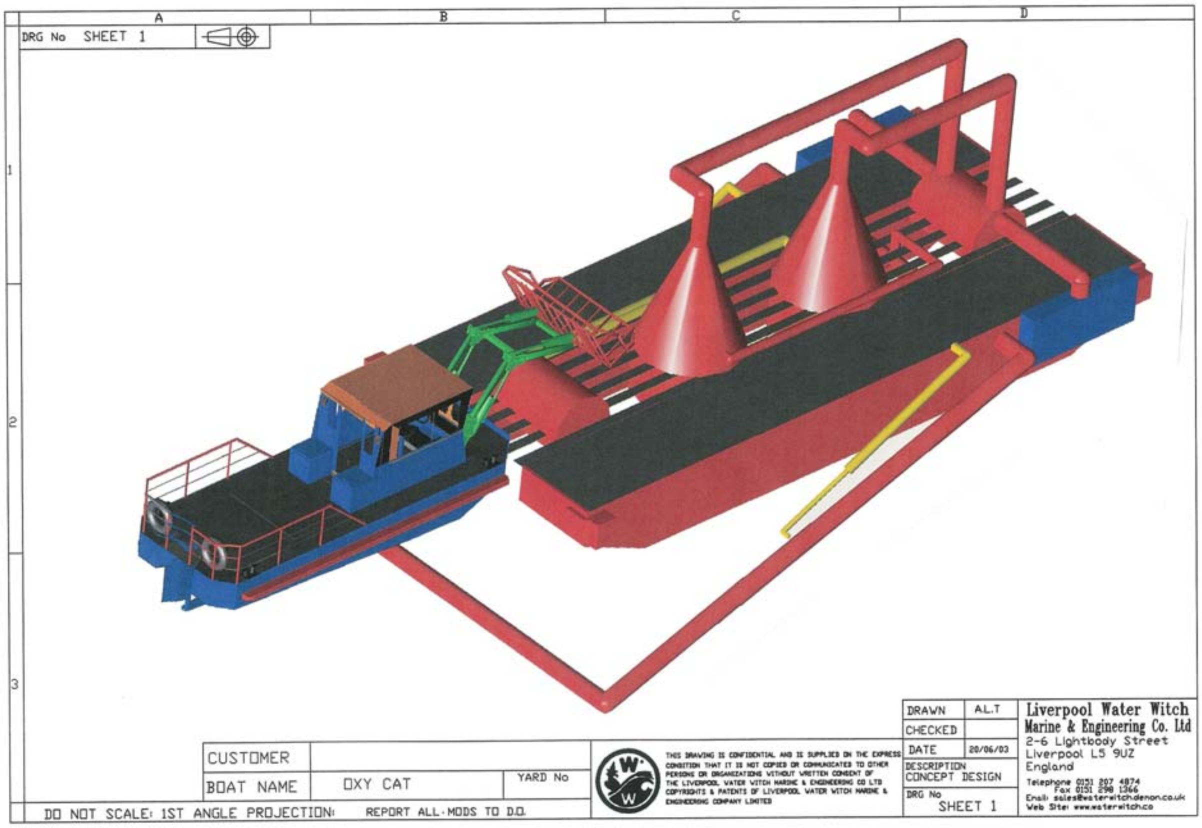
Not surprisingly, under the above modeling conditions, a vertical injection port (90 degrees) results in the highest vertical penetration of the water column (to 20 meters water depth), but then begins to sink and oscillate, reaching 100 percent dilution or approximately 7 parts per million dissolved oxygen (DO) only 10 meters horizontal distance from the diffuser. An injection port angle of 0 degrees reaches 100 percent dilution at 47 meters from the diffuser. There is no vertical penetration or oscillation. A 45-degree injection port angle penetrates 12 meters into the vertical and reaches 100 percent dilution at 37 meters horizontal distance from the diffuser. From a volumetric standpoint, the 45-degree geometry appears to oxygenate the largest water column volume.

Assuming an oxygen consumption rate of 0.2 milligrams per liter per day, a water current of 1 centimeters per second, and an initial DO concentration above ambient of 5 mg/L, a DO plume could theoretically travel 25 miles before the added DO was consumed in the canal bottom waters. However, this simple analysis neglects horizontal and vertical dispersion of the oxygenated plume into the canal waters as it advects through the canal. The end result is that a point injection of a highly oxygenated stream of water will likely affect DO levels over a wide spatial scale. This phenomenon was observed in Camanche Reservoir, where ambient currents in the bottom of the lake advected high DO water miles upstream of the oxygen injection point.

The following costs were provided by Richard Speece of ECO2Tech, Indianapolis, Indiana. A 12-foot-diameter cone delivers 20,000 pounds oxygen per day at a water depth of 100 feet and 40,000 pounds oxygen per day at a water depth of 200 feet. A 1-ton day above-ground cone with pump (excluding intake and outlet piping, oxygen and electricity) would cost approximately $100,000 to rent during the summer/fall.

Pressure swing oxygen production equipment will cost about $75,000 for each ton per day of capacity or $750,000 for a 10 tons per day VPSA system. This a complete cost. It will consume about 600 kilowatt hours per ton of oxygen produced.

A barge-mounted, 10 tons per day super-oxygenation system (Figure 3-5) would cost approximately $3,000,000. ECO2Tech has recently provided costs for such a barge to the city of Liverpool, England. Similar barge systems have been used for decades to oxygenate the River Thames in England, and a number of oxygenation barges are in use in China to oxygenate rivers during low DO episodes related to storm water runoff events.



Figures 3-5. Schematic of 10 Ton Per Day Oxygenation Barge
Courtesy of Dr. Dick Speece, ECO2Tech.

CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

Our analysis indicates that the Bubble Plume and Speece Cone oxygenation technologies are both viable options for targeted areas of ecological significance within Hood Canal, although we believe that the Bubble Plume System will require less capital equipment and less engineering than the Cone alternative (see Table 4-1). However, numerous implementation questions remain:

- What is the next step toward an oxygenation solution for Hood Canal? Should there be no action, a pilot project or construction?
- How will the preferred alternative be selected?
- What will be the size and operational window of the project?
- Will it be a permanent facility?
- Will equipment be leased or purchased?
- Where will it be located along or on the canal?
- What permits will be required?
- Who will prepare the engineering drawings and/or specification packages for bid? Only then will the actual costs of the project be known.

Table 4-1. Aeration/Oxygenation Technology Summary

System	Bubble plume system	Linear diffuser system	Cone system
Estimated cost of Pilot Study	1.4 ton per day system – $450,000	1.4 ton per day system - $400,000	6 ton per day system - $650,000
Extent of apparatus	Low–simple diffuser array. No pumps.	Moderate–fairly extensive lengths of linear diffuser may be required. No pumps.	Moderate–system requires submerged pump and underwater electrical line to cone.
Control of DO injection	Low/moderate–system results in oxygenation of upper water column. By controlling gas flow rate, elevation of DO injection (horizontal spreading of detrained oxygenated plume) can be somewhat controlled.	Moderate–DO tends to dissolve within 5 to 10 meters above the diffuser line.	High–system can be configured to inject DO at any point in system. Horizontal discharge allows for control of level at which DO is injected. System most appropriate when sediments need to be well oxygenated.
Effects on destratification	High–system must be designed and operated carefully so as to avoid destratification. System efficiency is depth dependent, so is not appropriate for shallow systems. System can be used as hybrid mixing/oxygenation system.	Low–gas discharge rate is very low and is well dispersed. System efficiency is depth dependent, so not appropriate for shallow systems.	Low–horizontal discharged promotes maintenance of thermal stratification.

In light of the above, it is our recommendation that the project proceed to the demonstration phase and that the Action Team, either by itself or in concert with a stakeholder group, select the preferred alternative and address the required siting questions. Once these issues are dealt with, a Request for Proposals could be issued for a preliminary design effort.

As described in this report, a number of large-scale systems have been used to oxygenate large lakes, reservoirs, and rivers throughout the world; although no studies involving deep, marine fjordal systems such as Hood Canal have been identified. Since aeration using pure oxygen is a proven technology, we are confident that a well-designed system could be installed in Hood Canal that would improve DO levels in targeted areas of the canal. One of the primary differences between existing systems and the Canal is its saline waters. Special attention would need to be paid to both corrosion and biofouling. Oxygenation would improve conditions for biota in the Canal while the hypoxia problem is being studied and source control strategies are being implemented. Such a system would be costly to implement, but the costs are reasonable when the areal extent of the Canal is considered.

A panel of experts is currently being convened to evaluate oxygenation options for Lake Onondaga, New York, a large and highly polluted lake in the Syracuse area. A pilot oxygenation system consisting of a 6 ton per day cone is planned for installation in the spring of 2006, and a potential full-scale system could consist of a total 6 oxygenation cones. This process could be used as a model for the development of a future Hood Canal pilot project.

CHAPTER 5
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APPENDIX A
HYPOLIMNETIC AERATION AND OXYGENATION OF SITES SOMEWHAT COMPARABLE IN BREADTH TO HOOD CANAL

Below is a detailed account of case studies in which aeration or oxygenation was implemented in lakes to improve water quality, and in many cases fish habitat quality. While numerous case studies have been documented, we have focused on studies in large, deep water bodies (depths greater than around 100 feet) which are more comparable to the deep-water environment of Hood Canal.

Wahnbach Reservoir, Germany

Wahnbach Reservoir (mean water depth = 19.2; maximum water depth = 43.0 meters; volume = 4.2×10^7 m^3, 33,700 acre-ft) serves as the source for drinking water and industrial processes in the Bonn-Siegburg area of northwestern Germany. Urban and agricultural development in the basin since the 1950's led to cultural eutrophication of the reservoir. In the early sixties, large blooms of the blue-green algae *Oscillatoria rubescens* began to appear. In addition, the monomictic lake exhibited hypolimnetic anoxia from August through November with a concurrent accumulation of up to 10 mg L-1 of manganese in the hypolimnion (Bernhardt 1975). Anoxic conditions also enhanced sediment P release increasing release rates from 0.03 mg-P m^{-2} day^{-1} under oxic conditions to 0.3-0.5 mg-P m^{-2} day^{-1} under anoxic conditions. No associated iron release was observed.

In response to degrading water quality, reservoir managers implemented a reservoir aeration project. In the summers of 1961-1962 and 1964, the reservoir was artificially destratified using compressed air. Summer destratification improved water quality but caused a substantial increase in water temperature. Water was deemed too warm for drinking water and industrial cooling uses. To avoid the increased temperature caused by artificial destratification, managers developed a hypolimnetic aeration system in 1966 which would maintain summer stratification. Cold hypolimnion could then be used as a potable water source.

From 1966-1970, an air-lift aeration system was installed, but it was not powerful enough to completely avoid anoxia and was enlarged in 1971 (Bernhardt 1975). The 1971 air-lift system consisted of a 40 meter by 2 meter diameter vertical tube with discharge outlets below the thermocline. Air injected at the bottom of the tube entrained hypolimnetic water which was aerated as it flowed up the tube. The system was later modified. Outlet ports in the vertical tube were closed, and the tube was connected to a separation chamber floating at the reservoir surface where air and other gasses could be degassed to the atmosphere. The aerated water then returned from the separation chamber to the hypolimnion via a 3-meter diameter tube with outlet ports into the hypolimnion. The system air flow rate of 7.0 m^3 min^{-1} induced a water flow rate of 432,000 m^3 day^{-1}. DO in treated hypolimnetic water increased 5 to 6 mg L^{-1}, resulting in an average oxygen delivery rate of 900 kg day^{-1}. Most of the oxygen transfer occurred in the bottom half of the contact tube where elevated hydrostatic pressure increased oxygen solubility, thereby enhancing oxygen transfer. The system's hypolimnetic cycling time was approximately 20 days, and its reported oxygen transfer efficiency was 50 percent.

Lake Cachuma, California

Lake Cachuma (mean water depth = 20.2 meter; maximum water depth = 58 meter; volume = 2.5 x 10^8 m^3, 202,800 acre-ft) is located in the Santa Ynez Mountains 40-km northwest of Santa Barbara, California, and serves irrigation, municipal and industrial demand in the surrounding area. The mesotrophic reservoir is monomictic, generally stratifying May through November, and is predominantly nitrogen limited. Hypolimnetic anoxia from July through November historically lead to degraded summer/fall water quality, including high concentrations of manganese, iron and sulfide.

From 1981-1984 the U.S. Bureau of Reclamation experimentally evaluated the effects of an aeration system on water quality in Lake Cachuma (Sartoris and Boehmke 1987). The system, installed near the dam, consisted of an air compressor connected to four PVC line diffusers suspended 9 to 12 meter above the bottom with floating barrels. The system reoxygenated the hypolimnion mainly by entraining oxygenated metalimnetic water into the hypolimnion via plume-induced mixing. The system can be classified as being in between a standard hypolimnetic aerator and an artificial destratification system. Operation of the aeration system weakened but maintained summer stratification.

Sartoris and Boehmke (1987) present limnological data for four treatment years (1981-1984). But they only present data for one pretreatment year (1980), thereby diminishing the weight of the study's conclusions. However, aeration appears to have substantially improved hypolimnetic water quality, with the greatest improvements observed in 1983-1984. Compared to the pretreatment year, the metalimnion expanded and the hypolimnion increased in temperature from 13 to 15 degrees C to 15 to 17 degrees C. The aeration system for the most part inhibited anoxia, and marginally increased hypolimnetic DO to above 1-2 mg L^{-1} in all treatment years. Slight anoxia was observed near the end of stratification in 1981-1982. Upstream of the dam, deep hypolimnetic water remained anoxic in 1981-1982, but full aeration of the hypolimnion was observed in 1983-1984. Fall oxidation reduction potential in the hypolimnion rose from around 0 mV in 1980 to above 300 mV for all treatment years.

Lake Baldegg, Switzerland

Lake Baldegg (mean water depth = 33 meter; maximum water depth = 66 meter; volume = 1.7 x 10^8 m^3, 137,900 acre-ft) is a large, deep, meromictic lake near Lucerne. The lake has experienced cultural eutrophication since the early 1900's (Imboden 1985). Eutrophication dramatically accelerated after the 1950s with the advent of modern agricultural, dairy and livestock operations. Between 1950 and 1975 lake TP content rose from 30 to 90 t. The lake exhibited both winter and summertime anoxia and high rates of internal P loading. Beginning in the 1950s, large blooms of the nuisance blue-green algae were common (Bürgi and Stadelmann 1991). Through the late 1960s and 1970s, a number of wastewater treatment plants were constructed, and non-point source control measures were implemented. As a result of external pollution control measures, TP content of the lake decreased to 50 t by the early 1980s.

In order to accelerate the pace of lake restoration lake managers installed a destratification/bubble plume oxygenation system in 1982 (Imboden 1985). The system consists of an oxygen tank and an air compressor onshore connected to 6 fine pore diffusers located near the bottom of the lake. Artificial mixing by compressed air is maintained from November through May by injecting 6 t d^{-1}

of air through 3-4 deep diffusers. Hypolimnetic oxygenation is operated from May through November with 3-4 t d^{-1} of oxygen injected through 4-6 diffusers.

Since 1983, DO levels in the hypolimnion have for the most part remained above 3 mg L^{-1} and TP content of the lake has decreased from 40 to 18 t (Gächter and Wehrli 1998). Since both external and internal P control measures were implemented concurrently, it is difficult to estimate the effects of oxygenation alone. Based on the brief data set presented by Imboden (1985), oxygenation appears to have decreased internal P loading. In 1982, the year prior to system operation, 7.0 t of TP was released from anoxic hypolimnion sediments. In the following two treatment years, internal TP release was 2.0-2.8 t. However, Gächter and Wehrli (1998) contend that observed TP decreases are solely the result of external controls.

While the effect of oxygenation on internal P loading is unclear, oxygenation did affect hypolimnetic ammonia and manganese (Gächter and Wehrli 1998). In the two years prior to treatment, maximum hypolimnetic ammonia was 1,500 μg-N L^{-1}. Post aeration maximum was 50 μg-N L^{-1}. This decrease occurred even though N loading was largely unaffected by external controls (Bürgi and Stadelmann 1991). Maximum manganese levels also decreased from 800 to 230 μg L^{-1}.

Richard B. Russell Lake, Georgia

Richard B. Russell Lake (mean water depth = 12 meter; maximum water depth = 47 meter; volume = 1.3×10^9 m^3, 1.07 million acre-ft) is a large peaking hydroelectric reservoir located on the Savannah River operated by the USACE. The reservoir was filled in 1983-1984, and as anticipated by lake managers, it exhibited hypolimnetic anoxia during the summer and fall of 1985 (James et al. 1985). Anoxia led to hypolimnetic accumulation of ammonia (100-800 μg-N L^{-1}), phosphate (50-150 μg-P L^{-1}), dissolved iron (2-10 mg L^{-1}), and manganese (1-3 mg L^{-1}). While the reservoir's main basin overturned in mid-December, water column DO did not reach saturation until late February due to the high DO demand of reduced compounds remaining in the water column. During 1984, because of its degraded quality, no hypolimnetic water was released from the reservoir.

Based on experimental work performed by the USACE in Thurmond Lake and extensive field monitoring during 1984, a fine bubble oxygenation systems was installed in the reservoir in 1985 (James et al. 1986). The system was sized to maintain 6 mg L^{-1} of DO in turbine releases of up to 1,700 m^3 s^{-1} (60,000 cfs). The system consists of an onshore oxygen storage facility that feeds two diffuser lines located 1.6 km upstream of the dam. The diffuser lines are 30 meter apart and are aligned parallel to the dam. Each line is 0.2 meter in diameter, approximately 400 meter long, and supports hundreds of 18 cm diameter ceramic and rubber diffusers. A second fine bubble diffuser system at the dam is operated under high flow conditions. The system has a peak oxygen delivery capacity of over 100 t d^{-1}.

Oxygenation, combined with higher rates of flushing as a result of power generation and the lower oxygen demand of aging inundated organic material, led to dramatic improvements in hypolimnetic water quality (James et al. 1986). In 1985, DO was maintained above 5 mg L^{-1} in most of the water column downstream of the oxygenation system, and thermal stratification was unaffected. Main basin levels of ammonia, phosphate, iron, and manganese all decreased 50-80 percent. Oxygen system transfer efficiencies ranged from 45-70 percent in 1985, while an intensive 1995 study estimated average system efficiency at 55 percent (Lemons et al. 1998). During the first few years of operation, oxygen demand steadily decreased with annual oxygen delivery dropping from 14,000 to 8,000 t from 1985 to 1987.

Amisk Lake, Alberta

Amisk Lake (mean water depth = 14.5 meter; maximum water depth = 60 meter; volume = 8.0 x 10^7 m^3, 65,000 acre ft) is a meromictic/dimictic lake located in central Alberta, Canada. The lake is long and narrow and has two main basins, a smaller north basin (maximum water depth = 34 meter, volume = 2.5x10^7 m^3) and a deeper south basin (maximum water depth = 60 meter, volume = 5.5x10^7 m^3). In the 1980s the lake exhibited common symptoms of eutrophication including high rates of internal nutrient loading, a declining cold-water fishery and noxious blooms of blue-green algae. In response to deteriorating water quality, an experimental hypolimnetic oxygenation project was initiated (Prepas et al. 1997, Prepas and Burke 1997). Full-scale, year-round hypolimnetic oxygenation began in the north basin in summer of 1990. The bubble plume oxygenation system consisted of an onshore liquid oxygen tank and evaporator, connected to a fine bubble diffuser system suspended 1 meter above the sediment near the deepest point of the basin. From 1990 through 1993, summer oxygen input ranged from 0.5-1.1 t d^{-1}. The project was terminated at the end of 1993.

Oxygenation had significant effects on water quality in the Amisk Lake's north basin. The clearest picture can be obtained by comparing pretreatment (1980-1987) and full treatment (1990-1993) mean summer water quality data. In the hypolimnion, P release decreased from 7.7 to 3.0 mg $meter^{-2}$ day^{-1}, and hypolimnetic TP decreased from 123 to 56 μg-P L^{-1}. Hypolimnetic ammonia decreased from 120 to 50 μg-N L^{-1} with no concurrent increase in hypolimnetic nitrate content. In the epilimnion, average summer TP decreased from 33 to 28 μg-P L^{-1}, ammonia decreased from 28 to 13 μg-N L^{-1}, and chlorophyll *a* decreased from 17 to 8 μg L^{-1}. A number of additional improvements relating to lake biota were observed. Summer phytoplankton biomass decreased and blooms were less dominated by blue-green algae (Webb et al. 1997). In addition, turbulence from the oxygenation system extended the period of spring mixing, thereby favoring a longer spring diatom bloom and delaying and diminishing subsequent blue-green algal growth. Researchers observed an increase in the abundance of deep-water *Daphnia* (Field and Prepas 1997). Finally, whole-lake fish biomass increased, as did the horizontal depth distribution of cold water fish when compared to pretreatment years (Aku and Tonn 1997, Aku et al. 1997).

Newman Lake, Washington

A restoration program for Newman Lake (mean water depth = 6 meter; maximum water depth = 10 meter; volume = 2.8 x 10^7 m^3, 23,000 acre-ft) was developed in the late 1980s to ameliorate eutrophic conditions including noxious blooms of blue-green algae, intense summertime hypolimnetic anoxia, a degraded cold-water trout fishery, and high rates of internal nutrient loading. Watershed best management practices were implemented, and in 1989 lake managers performed an alum treatment to promote the retention of P in lake sediment. To further improve water quality, hypolimnetic oxygenation was implemented using a Speece Cone in 1992 (Thomas et al. 1994).

The system consists of a submerged pump and inverted cone mounted on the bottom of the lake. Oxygen is piped to the chamber from two onshore molecular sieve O_2 generators. Highly oxygenated water is discharged horizontally into the hypolimnion through a 46-meters long diffuser pipe. The discharge helps to promote dilution of the highly oxygenated water while transporting oxygenated water horizontally into the hypolimnion. The oxygenation system is designed to add up to 2 t d^{-1} of oxygen to the lake. Flow rate through the chamber is 0.6 m^3 s^{-1}.

Oxygenation maintained an hypolimnetic DO of 5.5 mg L^{-1} throughout the summer and fall 1992. In the previous year the hypolimnion was anoxic late May through early August. Oxygenation resulted in induced oxygen demand (Moore et al. 1996). Pretreatment hypolimnetic oxygen demand was 915 kg d^{-1} while post oxygenation demand was 1,530 kg d^{-1}. To date, published data on the project emphasize the biological effects of oxygenation (Doke et al. 1995, Schumaker et al. 1993). Oxygenation expanded suitable trout habitat and increased benthos diversity.

Douglas Dam, Tennessee

Douglas Reservoir (mean water depth = 38 meter; volume = 1.7 x 10^9 m^3, 1.4 million acre-ft) is a very large power generation reservoir located on the French Broad River operated by the TVA. During the late summer, turbine releases from Douglas Dam historically contained low DO and noxious levels of hydrogen sulfide. To protect downstream biota and recreational facilities from degradation, reservoir managers installed a fine bubble oxygenation system in 1993 (Mobley and Brock 1995). The system includes 16 diffuser frames that are placed 200 to 300 meters upstream of the dam. Each frame measures 30 meters by 36 meters and supports 1,200 meters of porous hose. The hose is fed pure oxygen from an onshore facility that includes a 75 m^3 liquid oxygen storage tank and 10 evaporator units. Each frame contains buoyancy chambers that can be filled or emptied with water or air from shore. Operators can remotely control the buoyancy of a frame, and easily deploy or retrieve frames as need. Once in position, the buoyancy of a frame is made slightly positive, causing the frame to float above attached weights resting on the reservoir bottom. The system has a massive oxygen delivery capacity of nearly 100 t d^{-1}. Experimental operation of the system increased DO in turbine releases of 475 m^3 s^{-1} (17,000 cfs) by 2.5-3 mg L^{-1}. Oxygen transfer efficiency above 90 percent was observed. Oxygenation did not disturb thermal stratification and eliminated sulfide in turbine releases.

Camanche Reservoir, California

Camanche Reservoir (mean water depth = 17 meters; maximum water depth = 31 meters; volume = 5.1 x 10^8 m^3, 417,100 acre-ft) is a large eutrophic multi-purpose reservoir located in the western foothills of the Sierra Nevada Mountains operated by the East Bay Municipal Utility District (EBMUD). Immediately down stream of the reservoir is a fish hatchery that rears Chinook salmon and steelhead trout. Summertime hypolimnetic anoxia during drought years historically led to poor water quality supplied to the fish hatchery. The main water quality problem was hydrogen sulfide (Horne 1989).

In the spring of 1993, EBMUD installed a Speece Cone near the Camanche Reservoir dam (Horne 1995, Jung et al. 1998) to improve the quality of water delivered to the hatchery. Since the hatchery required cold water, a cone was selected because of the system's low potential for heating the hypolimnion due to metalimnetic entrainment or accidental destratification. The system is similar to that installed in Newman Lake, but larger. The horizontal diffuser is 30 meters long, 0.5 meters in diameter, and has 150 5 cm diameter discharge ports. Oxygen is supplied from an onshore liquid storage tank. The system supplies up to 8 t d^{-1} of oxygen at a pumping rate of 1 m^3 s^{-1}.

The system maintains DO levels above 5 mg L^{-1} at the dam and sulfide has not been detected at the hatchery since the system began operation in 1993 (Horne 1995). Spatial monitoring of DO in 1993-94 showed that a well-oxygenated plume of deep water migrated up the reservoir about 3 km after 40 days after oxygenation. Experimental short-term shutoff of the system in the summer of 1996 showed that oxygen demand in the hypolimnion increased from 0.07 mg L^{-1} d^{-1} before oxygenation to 0.12 mg L^{-1} d^{-1} during oxygenation (Jung et al. 1998). Operation of the system caused a slight degradation of the metalimnion and caused temperature in the bottom of the hypolimnion to increase from 13.5 to 15 °C.

Oxygenation appeared to improve reservoir water quality. Fall hypolimnetic ortho-P levels decreased from 200 μg-P L^{-1} prior to treatment to less than 50 μg-P L^{-1} after oxygenation. Fall hypolimnetic ammonia decreased from 1,000-1,700 μg-N L^{-1} to less than 200 μg-N L^{-1}. Hypolimnetic nitrate appeared to drop slightly after oxygenation. Since oxygenation was implemented, summer surface chlorophyll *a* has decreased from 40-50 μg L^{-1} to less than 10 μg L^{-1}. Average summer Secchi depth has increased from 1.5 to 5 meters.

APPENDIX B
HISTORICAL OVERVIEW OF AERATION AND OXYGENATION

The discussion below is extracted from an extensive review of lake aeration by Taggart and McQueen (1981). The reader is encouraged to consult that paper for more information and references.

Historical Overview of Lake Aeration

The first reported application of hypolimnetic aeration occurred in the 1940s in Lake Bret, Switzerland. Lake water was pumped from the hypolimnion to an onshore aeration basin, then discharged back to the hypolimnion. While relatively inefficient, the system maintained hypolimnetic DO levels at 2 mg L^{-1} causing a reduction in hypolimnetic iron levels. The first reported attempt at hypolimnetic aeration was attempted in 1963 in Lake Pfaffiker, Switzerland (Taggart and McQueen 1981). Air was pumped into a 30-meters long tube placed at the base of the hypolimnion. The top of tube was 2-meters below the surface, and as a result, hypolimnetic water was air-lifted into the epilimnion and ultimately the lake destratified prematurely. The first successful hypolimnetic aeration project began in Wahnbach Reservoir, Germany, in the early 1960s (Bernhardt 1975). The large reservoir (volume = 4.2×10^7 m^3, 33,700 acre-ft) experienced severe hypolimnetic anoxia and an associated degradation in hypolimnetic water quality. Summer stratification was required to maintain a cool hypolimnion raw water source. As a result, researchers developed a confined air-lift system which aerated the hypolimnion while maintaining stratification. The aeration system maintained year-round levels of DO in the hypolimnion and lowered hypolimnetic manganese and ortho-P concentrations.

The success at Wahnbach Reservoir spurred additional early project of smaller size in Europe and North America (Taggart and McQueen 1981). A number of small-scale experimental applications of hypolimnetic aeration were tested in North America in the early 1970s. The first was a small-scale system tested during the summer of 1971 in Hemlock Lake (volume= 3.5×10^5 m^3, 280 acre-ft), Michigan (Fast et al. 1973). The aeration system was similar in concept to that used in Wahnbach Reservoir, but much smaller in size. Aeration increased hypolimnetic DO, but leakage of the system promoted epilimnetic algal activity and caused the lake to prematurely overturn. A HELIXOR air-lift system was used in two large Wisconsin lakes, Fox Lake (volume= 6.1×10^7 m^3, 49,000 acre-ft) and Beaver Dam (volume= 5.9×10^7 m^3, 47,300 acre-feet). The system consisted of riser tube with a helix shaped plate twisting within the tube. The plate acted to increase contact time of the rising air-water plume, thereby increasing air dissolution into the water. In both lakes, the HELIXOR system lead to destratification in the same manner that occurred in Lake Pfaffiker. A HELIXOR full-lift aeration system with a separation box and return tubes was tested in three small Wisconsin lakes, Mirror (volume = 4.0×10^5 m^3, 324 acre-ft), Larson (volume = 1.9×10^5 m^3/152 acre-ft), and Silver (volume = 4.0×10^5 m^3, 324 acre-ft), between 1972-1973 (Smith et al. 1975). In Mirror Lake, the aeration system was undersized and hypolimnetic DO seldom exceeded 1 mg L^{-1}. In Larson Lake, aeration maintained hypolimnetic DO between 2-8 mg L^{-1}. Hypolimnetic ortho-P changed little, but fall ammonia levels dropped 85 percent with no concurrent increase in nitrate. Researchers noted that hypolimnetic oxygen demand increased three to four-fold during aeration. No water quality data was reported for Silver Lake.

LIMNO partial air-lift aerators manufactured by Atlas Copco of Sweden were installed and tested in a number of sites in the 1970s (Taggart and McQueen 1981). Managers performed a larger scale hypolimnetic aeration study in Lake Waccabuc, New York (volume= 4.1 x 10^6 m^3 = 3,300 acre-ft). Hypolimnetic DO levels increased in both years, but aeration decreased hypolimnetic accumulation of TP in only one year. Ammonia was unaffected in both years. Managers also monitored the effects of full-lift hypolimnetic aeration in Spruce Knob Lake (volume= 2.2 x 10^5 m^3 = 180 acre-ft), Virginia. One year of pretreatment data (1973) and two years of post hypolimnetic oxygenation data (1974-1975) are presented. While stratification was maintained, hypolimnetic temperature during aeration increased by 2-3 degrees. Aeration resulted in statistically significant drops in hypolimnetic ortho-P, TP and CO_2 and increases in nitrite and nitrate.

LIMNO aerators were also used in nine European lakes and reservoirs between 1972 and 1982. The most detailed case study concerned Sodra Horken, Sweden (area = 9.1 km^2). A LIMNO aerator was installed in a small, highly polluted basin of the oligotrophic lake. Aeration maintained hypolimnetic DO as high as 15-20 mg L^{-1}. Hypolimnetic P dropped from 0.4 to 0.05 mg-P L^{-1}, total inorganic nitrogen from 2.5 to 0.3 mg-N L^{-1}, and reduced iron from 0.2 to 0.01 mg L^{-1}. Fifteen LIMNO partial-lift hypolimnetic aerators were installed in hypereutrophic Lake Tegel (volume= 2.5 x 10^7 m^3, 20,300 acre-ft), Berlin, as part of a comprehensive restoration plan (Heinzmann and Chorus 1994). System operation began in 1980, however full operation of the system caused the lake to destratify. Since the late 1980s the system has been operated intermittently to avoid destratification. It appears that intermittent operation of the aeration system may decrease peak hypolimnetic total phosphorous concentrations. A smaller scale one-year aeration project was conducted in Weslinger See (volume= 1.05 x 10^6 m^3, 840 acre-ft), a small kettle lake located near Munich (Steinberg and Arzet 1984). Operation of a LIMNO system in 1981 caused a 50 percent decreased internal phosphorus loading. Higher summer phytoplankton biomass after aeration was attributed to increased eddy diffusion of nutrients from the hypolimnion to the epilimnion during aeration.

Beginning in the late 1970s, lake managers in British Columbia, Canada, installed and monitored a number of small-scale hypolimnetic aeration systems to improve the quality of cold water recreational fisheries in eutrophic lakes. In 1978-1979, Ashley (1983) performed a split-lake study in Black Lake (volume = 1.8 x 10^5 m^3,146 acre-ft). The study confirmed that oxygenation could inhibit hypolimnetic anoxia while maintaining thermal stratification. The study also documented interesting in-lake aquatic chemistry dynamics as a result of aeration. Degassing of CO_2 in the aeration system lead to a pH increase which prompted the co precipitation of ortho-P and magnesium with calcium carbonate. High pH also caused a dramatic drop in ammonia via volatilization in the aeration system. Additional studies have been conducted in Glen Lake and St. Mary Lake with the aim of developing and refining standardized design criteria for hypolimnetic aeration systems.

Finnish lake managers have developed the MIXOX oxygenation method and utilized it in over 50 lakes since 1981 (Lappalainen 1994). The MIXOX method pumps oxygen rich epilimnetic water into the bottom of the hypolimnion. Using appropriate pumping rates, the thermocline will rise and sharpen, but stratification will be maintained. After decreased wastewater loading and about a decade of MIXOX aeration in Lakes Sarkinen (volume = 2.5 x 10^6 m^3, 2,000 acre-ft) and Pyhajarvi (volume = 3.3 x 10^7 m^3, 26,800 acre-ft), summer hypolimnetic DO levels are now maintained above 4 mg L^{-1} and average summer epilimnetic TP has dropped from 20 to 13 ug-P L^{-1} and 90 to 35 ug-P L^{-1}, respectively. In Lake Huruslahti (volume = 2.7 x 10^7 m^3, 21,900 acre-ft), MIXOX aeration decreased average daily internal total phosphorous loading from 21.6 to 7.3 kg.

In the late 1980s the German company Petersen-Schiffstechnik developed a full-lift hypolimnetic aeration system named TIBEAN, a German acronym for Deep Water Aeration System. A submersible pump draws hypolimnetic water through a venturi tube. The water sucks in air from a "snorkel pipe" which extends above the lake surface. The air-water mixture is injected into the bottom of an air-lift tube which extends from the hypolimnion to the water surface. Aerated water is degassed at the surface then returned to the hypolimnion via a concentric outer tube which extended down into the hypolimnion. A deflector plate redirects returning aerated water horizontally into the hypolimnion. The TIBEAN reportedly has the lowest energy requirements of any documented hypolimnetic aeration system. The system's modular design allows for easy assembly, making transport and installation of the system simple and quick. TIBEAN has reportedly been used in Lakes Muggesfelde, Krupunder, and Terlago (Italy). In Lake Muggesfelde (volume = 2.7 x 10^6 m^3, 2,200 acre-ft), intermittent operation of the system in 1987 maintained hypolimnetic DO levels above 5 mg L^{-1} and decreased internal nutrient loading, but no water quality data was presented. TIBEAN was used in 1990 in Lake Krupunder (volume = 2.8 x 10^5 m^3, 230 acre-ft), a small urban lake near Hamburg. The system running at 25 percent capacity maintained hypolimnetic DO levels above 5 mg L^{-1}. However, hypolimnetic ortho-P levels still increased from 10 to 110 ug-P L^{-1} during the summer and fall. No pretreatment data were reported.

A handful of aeration projects have occurred in large southern California drinking water reservoirs. From 1981-1984 the U.S. Bureau of Reclamation experimentally evaluated the effects of aeration in Lake Cachuma (volume = 2.5 x 10^8 m^3, 202,800 acre-ft). The system consisted of an air compressor connected to PVC line diffusers suspended 9-12 meters above the lake bottom (Sartoris and Boehmke 1987). The aeration system increased hypolimnetic temperature, and weakened but maintained summer stratification. The aeration system for the most part inhibited anoxia, and marginally increased hypolimnetic DO to above 1-2 mg L^{-1} in all treatment years. Aeration caused a roughly 60 percent drop in hypolimnetic manganese, total phosphorous, and total inorganic nitrogen, and inhibited hypolimnetic sulfide accumulation.

In one of the few study that unequivocally demonstrated inhibition of sediment phosphorous release, Soltero et al. (1994) monitored the effects of hypolimnetic aeration in Medical Lake (volume = 6.2 x 10^6 m^3, 5,000 acre-ft), Washington. The authors statistically compared three years of pretreatment water quality data with data from one year of partial-lift LIMNO aeration and three years of full-lift aeration. Hypolimnetic TP was significantly lowered around 65 percent during both partial-lift and full-lift aeration. Hypolimnetic ammonia was also significantly lowered over 50 percent during partial-lift aeration. Ammonia data was not collected during operation of the full-lift aerator.

The effects of hypolimnetic aeration were extensively documented in two large Virginia drinking water reservoirs, Lake Prince and Western Branch Reservoir. Prior to aeration, hypolimnetic anoxia resulted in high hypolimnetic concentrations of iron and manganese. The high chlorine dosage needed to oxidize these reduced compounds lead to high trihalomethane levels in finished drinking water. In the early 1990s aerators were installed at the dam end of the reservoirs. Aeration had marginal impacts on hypolimnetic DO levels and enhanced mixing in both reservoirs. Aeration lead to the partial destratification of Western Branch Reservoir. In Prince Lake, hypolimnetic iron, TP, ammonia and sulfide dropped during aeration. In Western Branch Reservoir, hypolimnetic iron, manganese, TP and sulfide dropped. DO and water quality improvements were to large extent spatially restricted to near the aerators.

Historical Overview of Lake Oxygenation

The discussion below is expended from an extensive review of lake oxygenation by Beutel and Horne (1999). The reader is encouraged to consult that paper for more information and references. Hypolimnetic oxygenation is a relatively new aeration technique used to prevent hypolimnetic anoxia. Lake oxygenation systems generally consist of a liquid oxygen storage facility on shore. Evaporators transform the liquid oxygen to gas, and the gas is dissolved into lake water through an on-shore contact chamber, a system of diffusers located under water, or a contact chamber submerged in the lake. Like hypolimnetic aeration, it preserves thermal stratification, however pure oxygen rather than air is used. As a result of higher oxygen solubility and higher system transfer efficiencies, the size of the mechanical devices and recirculation rates needed to deliver an equivalent amount of oxygen using pure oxygen rather than air are greatly reduced. This avoids a number of the disadvantages associated with traditional aeration systems. Lower recirculation rates minimize turbulence introduced into the hypolimnion, thereby minimizing induced oxygen demand and the chance of accidental destratification. High oxygen delivery rates and low induced oxygen demand allow for the maintenance of high levels of DO in oxygenated hypolimnia throughout the stratified period (Thomas et al. 1994, Horne 1995, Prepas and Burke 1997). Additional advantages of hypolimnetic oxygenation include avoidance of hypolimnetic dissolved nitrogen supersaturation (Fast et al. 1975), low energy use (Speece 1994), and low commercial oxygen costs. Four main types of oxygenation systems are currently in use: side stream oxygenation, bubble plume oxygenation, diffuse deep-water oxygenation, and submerged contact chamber oxygenation.

The first oxygenation systems were developed in the 1970s. Some early oxygenation systems used side stream oxygenation, in which hypolimnetic water is pumped onto shore, injected with oxygen, then discharged back into the hypolimnion (Fast et al. 1975, Fast et al. 1977). A major draw back of this system is the high energy costs associated with the maintenance of a pressurized chamber on shore. Thus, this system is not commonly used for hypolimnetic oxygenation. In the early 1970s, the Tennessee Valley Authority (TVA) began examining the feasibility of oxygenation for reaeration of hydroelectric reservoir discharges with low DO at Fort Patrick Henry Dam, Tennessee (Nicholas and Ruane 1975). They used diffuse deep-water oxygenation consists of an extensive network of linear diffusers that release fine oxygen bubbles that rapidly dissolve into the overlaying water column. A prototype submerged contact chamber oxygenation system consisting of a submerged cone-shaped contact chamber with A submersible pump draws water from the hypolimnion into the top of the cone was developed by Speece et al. (1971). Speece et al. (1971) observed oxygen transfer efficiency in the range of 80-90 percent. With the proper horizontal dispersion of reoxygenated water, a submerged chamber system can overcome potential limitations of a bubble plume or diffuse deep-water system. These include accidental destratification caused by oxygen bubbles rising through the thermocline (Speece 1994) and localized anoxia as a result of limited oxygen dispersion within the hypolimnion (Fast and Lorenzen 1976). In addition, in contrast to bubble plume and diffuse deep-water systems, horizontal dispersion sends reoxygenated water out over the sediments of the reservoir, thereby keeping highly oxygenated water in direct contact with the sediments and assuring a well-oxygenated sediment-water interface.

In the 1980s, Swiss lake managers developed bubble plume oxygenation, which works by injecting pure oxygen through a dense group of diffusers at the lake bottom (Imboden 1985, Gächter and Wehrli 1998). Oxygen bubbles dissolve into a surrounding plume of rising water. The oxygenated plume then detrains and spreads out horizontally below the thermocline. In Lake Baldegg (137,900 acre-ft), the system consists of an oxygen tank and an air compressor on shore connected to six diffuser arrays located near the bottom of the lake. Artificial mixing via compressed air is maintained from November through May by injecting 6 metric tons per day (t/d) of air through 3 to 4 deep diffusers. Hypolimnetic oxygenation is operated from May through November with 3 to 4 t/d of oxygen injected through 4-6 diffusers. Phosphorus release is still observed during the summer, but oxygenation did cause a decrease in hypolimnetic accumulation of ammonia and manganese (Gächter and Wehrli 1998). In some lakes, the system appears to have trouble maintaining a well oxygenated sediment water interface because most of the oxygen is distributed to the upper levels of the hypolimnion (McGinnis, personal correspondence). This appears to be a major drawback of the bubble plume oxygenation system.

Oxygenation came of age in the 1990s. A diffuse bubble plume system now in operation at Douglas Dam, Tennessee (1.4 million acre-ft) has successfully oxygenated large turbine discharges since 1993 (Mobley and Brock 1995). The reservoir is a large power generation reservoir located on the French Broad River. During the late summer, turbine releases from Douglas Dam historically contained low DO and noxious levels of hydrogen sulfide. The system has 16 diffuser lines that include 1,200 meters each of porous hose. The hose is fed pure oxygen from an on shore facility that includes a large capacity liquid oxygen storage tank and multiple evaporator units. Each oxygen line contains buoyancy chambers that can be filled or emptied with water or air from shore. Operators can remotely control the buoyancy of a frame, and easily deploy or retrieve frames as need. Once in position, the buoyancy of a frame is made slightly positive, causing the frame to float above attached weights resting on the reservoir bottom. The diffuse deep-water oxygenation system has a few advantages over other systems. In contrast to contact chambers, the system does not require the pumping of water. In addition, unlike the bubble-plume oxygenation system, the system does not induce large-scale vertical current of water. Thus, dissolved oxygen tends to stay deeper in the reservoir. The system at Douglas Dam has a massive oxygen delivery capacity of nearly 100 t/d. Experimental operation of the system increased DO in turbine releases of 17,000 cfs by 2.5-3 mg/L. Oxygen transfer efficiency above 90 percent was observed. Oxygenation did not disturb thermal stratification and eliminated sulfide in turbine releases. Smaller scale (5-15 t/d) diffuse deep-water oxygenation systems have been installed in a number of California drinking water reservoirs including Los Vaqueros (100,000 acre-feet) operated by the Contra Costa Water District and Upper San Leandro (40,000 acre-feet) operated by East Bay Municipal Utility District). Others systems are being planned for drinking water reservoirs operated by the San Francisco Public Utility Commission and the San Diego Water Department.

Submerged contact chamber oxygenation system have been installed in two lakes, Newman Lake, Washington and Camanche Reservoir, California (Speece 1994, Horne 1995) to improve cold water habitat for fish. In Newman Lake (23,000 acre-ft), oxygen is piped to the chamber from two on shore molecular sieve oxygen gas generators. Highly oxygenated water is discharged horizontally into the hypolimnion through a 46-meters long diffuser pipe. The discharge helps to promote dilution of the highly oxygenated water while transporting oxygenated water horizontally into the hypolimnion. The oxygenation system is designed to add up to 2 t/d of oxygen to the lake. Flow rate through the chamber is 0.6 m^3/s. Oxygenation maintained an hypolimnetic DO of 5.5 mg/L throughout the summer and fall 1992. In the previous year the hypolimnion was anoxic late May through early August. Oxygenation expanded suitable trout habitat and increased benthos diversity (Doke et al. 1995, Moore et al. 1996).

Camanche Reservoir (417,100 acre-ft) is a multi-purpose reservoir operated by the East Bay Municipal Utility District. In 1993, a submerged contact chamber oxygenation system was installed to improve the quality of water delivered to a nearby fish hatchery that rears Chinook salmon and steelhead trout. The system is similar to that installed in Newman Lake but oxygen is supplied from an on shore liquid storage tank and the system is larger. It supplies up to 8 t/d of oxygen at a pumping rate of 1 m3/s. The system maintains DO levels above 5 mg/L at the dam and sulfide has not been detected at hatchery since the system began operation. Spatial monitoring of DO in 1993-94 showed that a well-oxygenated plume of deep-water migrated up the reservoir about 3 km after 40 days after oxygenation. Oxygenation has had dramatic effects on water quality in Camanche Reservoir (Jung et al. 1998). Fall hypolimnetic orthophosphate levels dropped from 200 ug-P/L prior to treatment to less than 50 ug-P/L after oxygenation. Summertime accumulation rates of phosphate in the hypolimnion dropped from 4-5 mg-P/m2/d to less than 0.7 mg-P/m2/d. Fall hypolimnetic ammonia dropped from 1,000-1,700 ug-N/L to less than 200 ug-N/L. This is equivalent to a drop in the rate of ammonia accumulation from 25-30 mg-N/ m2/d to less than 4 mg-N/ m2/d, with no concurrent increase in the rate of nitrate accumulation. Since oxygenation was implemented, peak chlorophyll a has dropped from 40-50 ug/L to less than 10 ug/L. Average summer secchi disk has increased from 1.5 to 5 meters.

A U-tube side stream oxygenation system has been developed by Speece (1996) for uses in rivers and shallow lakes that avoids this operational cost. Low DO water is diverted on shore and discharged into a 175-foot-deep U-tube. Oxygen gas is then injected into the water at the bottom of the tube. The hydrostatic pressure in the tube promotes the dissolution of oxygen gas into the water and DO concentration in the water discharged back into the river is around 50 mg/L. Use of U-tube systems instead of an on shore pressurized chamber can decrease electrical costs by a factor of 20.